Volume XII: Number 1 (2001)

Human Systems IAC

GATEWAY

Published by the Human Systems Information Analysis Center, formerly known as CSERIAC

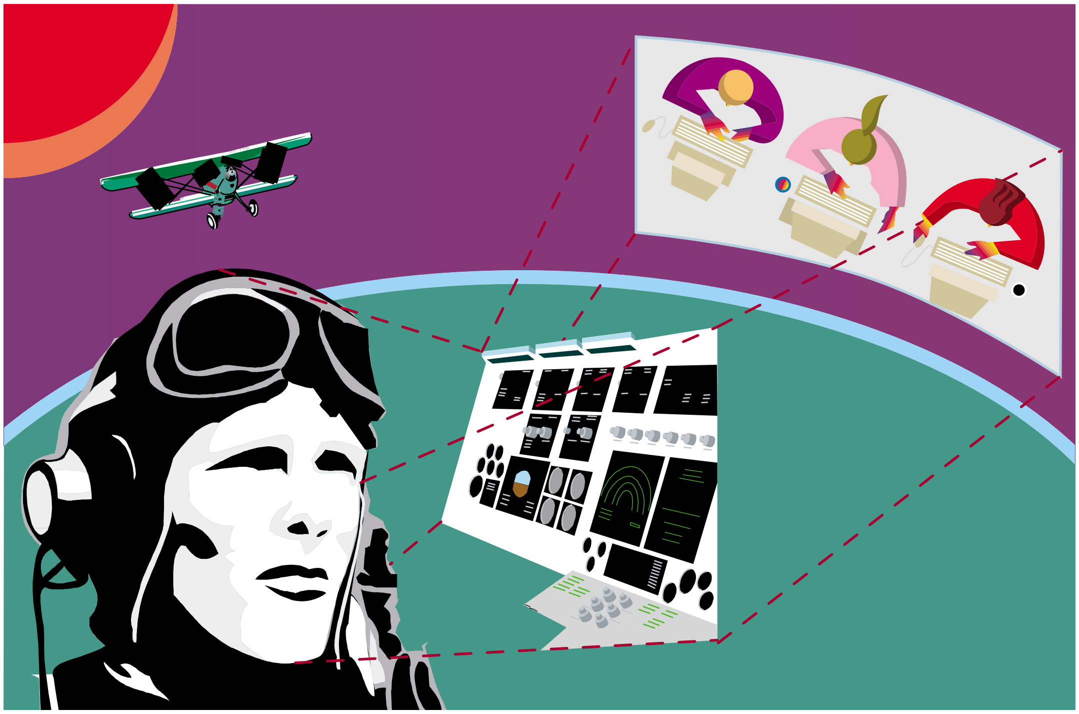

Figure 1. Conceptualization of the complex aviation environment of the 21st century.

Cognitive Systems Engineering in Military Aviation Domains: An Introductory Primer

Michael D. McNeese and Michael A. Vidulich

It is our privilege to welcome you to a special issue of the *HSIAC Gateway* that introduces readers to cognitive systems engineering (CSE) as it relates and applies to military aviation domains. In this issue we provide a broad sampling of perspectives, issues, methods, and applications that afford a first-look understanding of CSE for use within aviation fields of practice. There will be nine separate synopses provided to whet your interest in the forthcoming HSIAC state-of-the-art report (SOAR), *Cognitive Systems Engineering in Military, Aviation Domains: Avoiding Cogminutia Fragmentosa!* (McNeese & Vidulich, Eds., 2001). Each article summarizes a chapter to appear in the report. Now take a closer look at what one may expect for the special issue—and in turn the SOAR.

Complex environments of the 21st century place workers in an information-rich world (see Figure 1) with little time to make sense out of events surrounding them, assess their plans, make appropriate decisions, or perform multiple activities. In many cases, computational support and advanced interfaces for work activities have not been engineered with cognition or context in mind. Unfortunately, this lack of "cognitive engineering" may produce what we refer to as *cogminutia fragmentosa*, where the worker's cognitive world breaks down into small, isolated strands of thought as unanticipated events transpire (mental stovepipes). There can be a loss of mean-

continued on next page

inside:

Special Issue: Cognitive Systems Engineering

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (FROM - TO)
01-01-2001	Newletter	xx-xx-2001 to xx-xx-2001

4. TITLE AND SUBTITLE
Gateway Volume XII: Number 1 (2001)
Unclassified

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
McNeese, Michael D ;
Vidulich, Micael A ;
Reising, John M ;
Eggleston, Robert G ;
et. al, ;

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME AND ADDRESS
Human Systems IAC
AFRL/HEC/HSIAC
2245 Monahan Way Bld 29
WPAFB, OH45433-7008

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME AND ADDRESS
,

10. SPONSOR/MONITOR'S ACRONYM(S)
11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APUBLIC RELEASE
,

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This newsletter contains information on Aviations Systems, Cognitive Engineering, Cognitive Systems and how they should be engineered for aviation domains, balancing research and design, Cognitive Work Analysis for Air Defense Applications in Australia, Cognitive Cockpit Engineering, and Analyszing te Cognitive System from a Perceptual Control Theory Point of View. The letter also has a calendar of upcoming, human systems events.

15. SUBJECT TERMS
cognitive engineering; cognitive engineering; work analysis; air defense; cockpit; HSIAC collection

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19. NAME OF RESPONSIBLE PERSON
			Same as Report (SAR)	24	Darrah, Sara Sara.Johnson@wpafb.af.mil
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER International Area Code Area Code Telephone Number DSN

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39.18

continued from previous page

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Michael A. Vidulich, Ph.D., is with the Human Technology Interface Branch, Crew System Interface Division, Human Effectiveness Directorate, U.S. Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio. His research has focused on the assessment of operator/pilot mental workload and situation awareness. As the U.S. Air Force representative to the TTCP HUM TP–7 Panel, he was the host of the Panel's meeting in Dayton in May 2000.

ing or control as the worker becomes separated from the demands of his or her work and may remain lost in terms of comprehending the emerging elements of a situation. When cogminutia fragmentosa persists, there is no longer an *interface* between the worker's cognitive world and the work for which he or she is responsible. In other words, the worker cannot properly adapt to the situation encountered (i.e., a maladaptive state exists). If this state continues, errors, failure, and even catastrophic disasters are highly probable. This state may also contribute to affective and emotional responses (e.g., fear, anxiety, rage) that further complicate agent-environment transactions. However all is not lost. We are now at a point in history where it is not uncommon to observe human factors practitioners referring to "cognitive systems engineering" as their method or tool of choice to respond to work environments that produce cogminutia fragmentosa. Indeed, as first-of-a-kind cognitive systems are proposed for complex environments, such as in military aviation domains, CSE is frequently utilized to understand and analyze various components of operator or team expertise (e.g., cognitive skills, engagement rules, specific knowledge), and the interaction of expertise with specifications of the work domain. As CSE is applied to real-world settings, agent-environment transactions can be quantitatively or qualitatively modeled (represented) and then used as a basis to predicate elements of a design (e.g., a human-computer interface or a decision-support system). Typically, CSE practitioners engage workers through a variety of CSE methods that capture multiple facets of how work is transacted from agents to environment.

This special issue highlights the perspectives and foundations of an international community of practitioners who have both developed and applied CSE. One can see the field emerges from several corridors that in turn produce alternative methodologies/approaches to address military aviation domains. Differing philosophies and techniques spawn incisive pathways of integration in the development of design artifacts. Because the aviation domain is fraught with multifarious levels of complexity and is demonstrative of cogminutia fragmentosa, we believe it supplies an excellent foundation for reviewing, assessing, communicating, and evaluating some of the principles (and nuances) inherent within various programs of CSE. The SOAR will emulate this objective by presenting nine chapters in the following three sections for readers (along with the respective first author of each chapter):

- Foundations and Perspectives (Reising, Eggleston, McNeese, Woods)
- Methodological Pursuits (Roth, Naikar, Hendy)
- Innovations, Integration, and Application (Taylor, Hudlicka)

The forthcoming synopses briefly traverse these sections and broadly define the waypoints of the SOAR, hence providing readers with an informed introduction to our special issue topic. They challenge the reader to contrast/compare philosophies of use, theories of origin, goals, benefits, methods, tools, experiences, constraints and problems of applications, lessons learned, and examples as a means to generate new levels of understanding—as they relate to the specific constraints encountered in military aviation.

Acknowledgments

This special issue and the forthcoming HSIAC SOAR is predicated on and developed in part, from an international symposium, *Cognitive Systems Engineering in Military Aviation*, cosponsored and organized under the auspices of the five-nation (U.S., UK, Canada, Australia, New Zealand) forum for international research collaboration, *The Technical Cooperation Program* (TTCP). The symposium was held in conjunction with the ninth annual meeting of TTCP Group HUM (Human Resources and Performance), Technical Panel 7 (TP7) Human Factors in Aircraft Environments, hosted by the U.S. Air Force Research Laboratory (AFRL) and held in Dayton, Ohio, USA, 22–26 May 2000. The purpose of TTCP HUM TP7 is to facilitate collaborative research and information exchange on human factors issues relevant to the extension of operational performance of advanced military aircraft. This symposium provided a timely opportunity to bring together key researchers and human factors specialists to discuss recent developments in cognitive systems engineering and to consider the implications for human factors issues in aircraft environments.

The international symposium and the year 2000 meeting of the TP–7 Human Factors in Aircraft Environments panel were financially supported by the Crew System Interface Division of the U.S. Air Force Research Laboratory (AFRL/HEC, Mr. Maris Vikmanis, Division Chief).

http://iac.dtic.mil/hsiac

Cognitive Engineering and its Relationship to Future Aviation Systems

John M. Reising

John Reising, Ph.D., is with the Crew System Interface Division, Human Effectiveness Directorate, U.S. Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio.

The theme of cognitive systems engineering (CSE) presupposes two things: first, that military aviation systems are susceptible to *cogminutia fragmentosa*; second, that the application of cognitive systems engineering to the design of military aviation systems is a likely palliative for the problem. Each of these presuppositions requires independent consideration. The focus here is on the viability of the assumption that the design of military aviation systems could promote cogminutia fragmentosa. In considering this issue, it will be suggested that not only is cogminutia fragmentosa a risk in current military aviation systems, but that the technological trends are making it an increasing risk in the future.

One of the hallmarks of cogminutia fragmentosa is that the user of a system cannot effectively adapt to encountered situations. This inability is due to a mismatch between the human's understanding of the current situation's properties, potentiality, and constraints and the actual state of the real world. Such mismatches are certainly present in today's military aviation systems.

One of the best examples of the problem is the difficulty that has been experienced in effectively using automation to aid pilots. A common problem with the implementation of aviation automation has been the moving of the pilot further and further out of the aircraft's direct control loop. In some cases the pilot became a relatively inactive partner of the automated system in the control of the aircraft. All often appeared to be fine, until something unexpected occurred. The automated systems could not be designed to deal with unexpected situations and the "out-of-the-loop" pilot was suddenly confronted with a bad situation with little or no knowledge of how it came to occur. Although this problem has been under consideration since World War II, there has not been any definitive solution found for even the current generation of relatively simple automated aids.

Previously, automation was largely used to control little more than the aircraft's flight path. Currently, automation is taking over many more tasks in the cockpits of such aircraft as the Royal Air Force's GR–1 Tornado and the U.S. Air Force's F–15E Strike Eagle. This change in the role of automation from simple aids for specific tasks to complicated collections of automated aids that participate in a multitude of the pilot's tasks, has effectively made automation a part of the aircraft's crew. Problems occur because the pilots and flight crewmembers often do not understand what the automation is doing or why. Much precious time and effort must be expended in analyzing the actions of the automation, rather than in adapting to the current mission situation. In other words, automation is often a bad team member that promotes cogminutia fragmentosa.

To improve this situation, automation must become more sophisticated in its interactions with the human team members. This more sophisticated and cooperative future automation has been referred to as an "electronic associate" (EA). Designing the EA demands a much better understanding of the human crew so that the EA can work well with the crew. Cognitive systems engineering may provide the insights to accomplish this goal. It is vital that useful tools for avoiding cogminutia fragmentosa be developed and validated because pilots of future military aircraft (such as the F–22) will be confronted with even more capable and complex systems to control. Also, some future systems, such as the uninhabited combat aerial vehicle (UCAV) (see Figure 1), will be moving the operator completely out of the aircraft. The operators of such systems need the automation controlling the systems to be a dependable partner. Using cognitive systems engineering should be tested as a means for designing such challenging and important future systems. ■

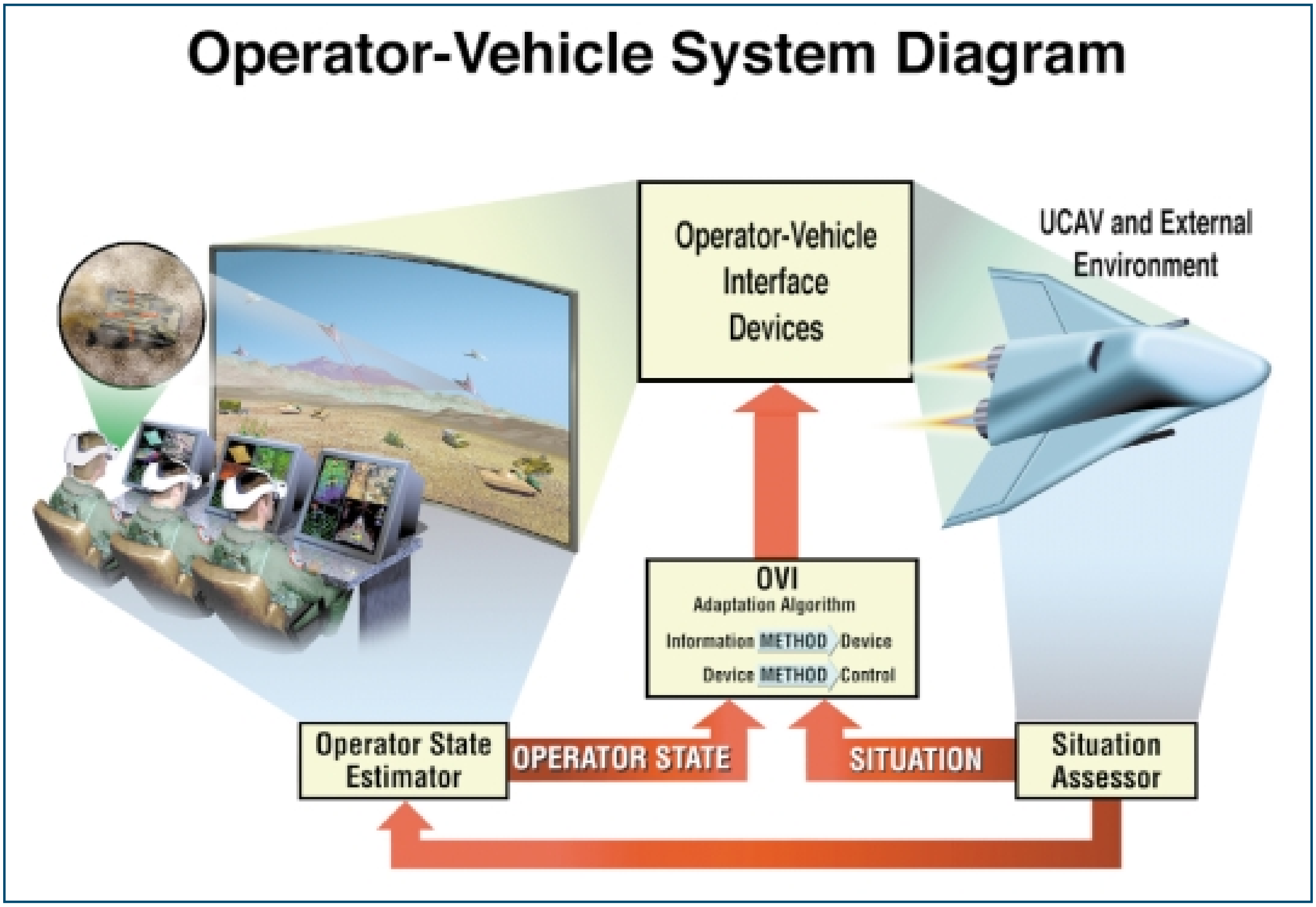

Figure 1. Adaptive UCAV system diagram.

HSIAC Pulse Check Reflected by Web Site

The HSIAC Web site, hosted by the Defense Technical Information Center (DTIC), at http://iac.dtic.mil/hsiac, is growing and expanding in scope. Changes to this site have been dramatic and reflect the activity going on at the Human Systems IAC.

The major driving force behind the redesign is the expanded scope of the IAC's subject areas, which are called Domains. Our charter now includes eleven domains of expertise including:

1. Human Systems Integration,
2. Habitability,
3. Human Factors,
4. Safety,
5. Health Hazards,
6. Medical Factors,
7. Personnel Survivability,
8. Manpower,
9. Personnel,
10. Training,

and the previous three (8, 9, 10) combined as 11, MPT.

The Human Systems IAC has specific areas of specialized knowledge referred to as Pillars. We currently sponsor a Pillar in the area of spatial disorientation (SD) countermeasures by working with the Air Force Research Laboratory and Veridian Engineering. The SD pillar can be accessed from the IAC web page from http://www.spatiald.wpafb.af.mil, This growing site is loaded with current information on spatial disorientation and will display the results of ongoing and developing research for many years to come.

Other changes to the web site include sites where free information, such as specifications, standards, handbooks, magazines, etc. on our various domains can be obtained. This information is provided in the form of links. Summarized HSIAC product information and a section called IAC success stories highlighting HSIAC's activities will soon be available.

http://iac.dtic.mil/hsiac

The State of Cognitive Engineering: A Retrospective-Based Analysis

Robert G. Eggleston

Cognitive systems engineering (CSE) is a multidisciplinary field that is both a scientific endeavor and an engineering practice that emphasizes human-centered analysis and design. I have recently completed an assessment of the state of the CSE field by way of an informal retrospective analysis. This analysis, extending back to the origins of CSE, considers the field from three different perspectives: conceptual foundations, engineering tools and practices, and the state of deployment. Some unique features of the analysis include:

- Depiction and contrast of several different CSE frameworks motivated by different theoretical positions and applied interests;
- Emphasis on both theoretical factors and engineering factors of CSE; and
- A brief look at issues in the deployment of CSE across the full spectrum of analysis, design, and evaluation components of development, including impediments to progress in using CSE concepts, tools, and methods.

This article is a brief synopsis of the retrospective analysis of CSE.

A central theoretical focus of CSE is *the study of work representations directly useful for design engineering*. As an engineering practice, it formulates human-centered work analyses, design concepts, and methods to facilitate integration of CSE products into large-scale system engineering practices (see Figure 1).

The conceptual foundations of the CSE field consist of different frameworks for modeling work. Four CSE frameworks or genotypes, championed by Card (see Eberts, 1997), Norman (1986),

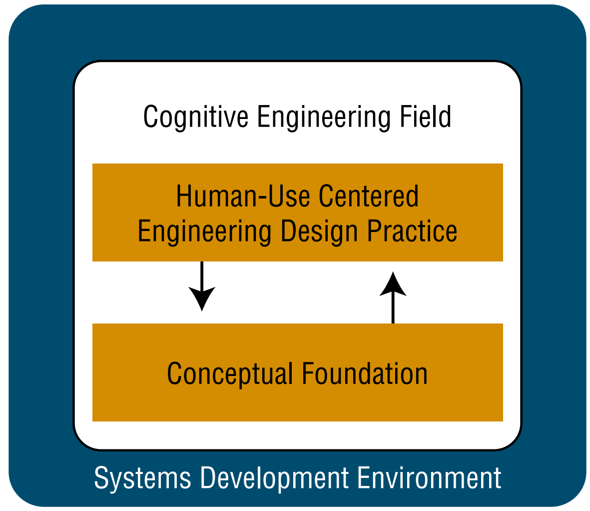

Figure 1. The field of Cognitive Engineering is both an engineering practice and an applied science in the context of system development.

Rasmussen (1988), and Woods (see Woods & Roth, 1998), serve to represent the scope of the CSE conceptual landscape. In general, these frameworks place different emphasis on modeling work as a property of (1) an agent, (2) a task, or (3) a constellation of agent, task, and environmental factors.

The creation of these CSE genotypes in and of themselves indicates progress in the field. Each of them provides a systematic and comprehensive conceptualization of how to model work. Some frameworks follow a cognitivist perspective, which emphasizes modeling goal-directed cognitive work in information processing terms. Others employ an ecological perspective that regards cognitive work as distributed over environmental and agent factors, and that assigns more importance to understanding the co-evolution of problem formation in work and ways to solve the dynamically evolving work problem.

Currently, the state of the various genotypes vary widely in terms of construct specificity and deployment guidance. In general, the CSE genotypes originating with Card (cognitivist) and Rasmussen (ecological) have been refined to a greater extent than those pioneered by Norman and Woods.

The Field of Cognitive Engineering

Conceptual Foundations	Engineering Practices	Complete integration into system engineering development process
1980s	1990s	20XX
• CE frameworks • Theories of work modeling	• New tools/methods (knowledge capture) • CE support aids	• Improved integration in total system engineering?
• Clarity of constructs (wide variation) • Ambiguities in use • Inconsistencies in use	• Limited life cycle attention • Reliability (open issue) • Persistent gap (analysis to design)	

Figure 2. Gains and limitations of cognitive engineering over its history of development.

It is very difficult to elicit and crisply represent information from subject-matter experts that capture the cognitive nature and demands of work. Considerable attention has been directed toward the development and refinement of new cognitive task analysis methods and tools to improve the CSE field. In general, many new probe techniques have been developed and used that have revealed new insights into work. These range from techniques that focus on extracting expertise to methods that assess different forms of problem solving and decision making to integrated suites of tools that attempt to provide a more comprehensive picture of cognitive work. However, to date, only limited attention has been directed toward the reliability of tool use and the reusability of the resultant outcome products over a system's life cycle. Further, the gap between CSE-based human-centered analysis and CSE guides to innovative artifact design still remains large.

CSE concepts and methods have enjoyed an increasingly wide use in system engineering in recent years. This attests to the perceived value of CSE. But on the negative side, perhaps the largest challenge to the CSE community is the need to improve clarity and reduce ambiguity and inconsistencies in use of CSE constructs and methods. Confusions between new CSE methods and older human factor methods for requirements analysis abound. Further, technical distinctions across CSE genotypes do not always appear to be well understood and followed, both within and between different genotypes. These represent serious impediments to the continued growth of the field.

In sum, while CSE has made a great deal of scientific and engineering progress over twenty some years, there are areas that need more refinement before CSE is likely to increase its impact on system development (see Figure 2).■

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Woods, D. D., & Roth, E. M. (1998). Cognitive Systems Engineering. In M. Helander (Ed.), *Handbook of human-computer interaction*. Amsterdam: Elsevier.

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calendar

may

Reno, NV, USA. May 6–9, 2001.
ASMA 2001: Aerospace Medical Association Meeting
Contact ASMA, 320 South Henry Street, Alexandria, VA 22314–3579, USA.
Tel: +1–709–739–2240, Fax: +1–703–739–9652, URL: http://www.asma.org

Colorado Springs, CO, USA. May 14–17, 2001.
46th Biennial Meeting of the U.S. Department of Defense Human Factors Engineering Technical Advisory Group
Contact Sheryl Cosing, 10822 Crippen Vale Court, Reston, VA 20194, USA.
Tel: +1–703–925–9791, Fax: +1–703–925–9644, E-mail: sherylynn@aol.com,
URL: http://dticam.dtic.mil/hftag/. *Meeting is open to all government personnel and others by specific invitation*.

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San Jose, CA, USA. June 3–8, 2001.
SID 2001: Society for Information Display
Contact SID, c/o Palisades Institute for Research Services, Inc., 411 Lafayette Street, 2nd Floor, New York, NY 10003, USA. Tel:+1–212–460–8090, Fax: +1–212–460–5460,
E-mail: wklein@palisades.org, URL: http://www.sid.org

Fairfax, VA, USA. June 4–7, 2001.
XV Annual International Occupational Ergonomics & Safety Conference
Contact Paul Champney. Tel: +1–509–786–4689, E-mail: pchamp@quicktel.com,
URL: http://www.ISOES.org

Miami Beach, FL, USA. June 4–7, 2001.
Intelligent Transportation Society of America's 11th Annual Meeting and Exposition
Contact ITS America, 400 Virginia Avenue, SW, Suite 800, Washington, DC 20024–2730.
Tel: +1–202–484–4847, Fax: +1–202–484–3483, URL: http://www.itsa.org

Arlington, VA, USA. June 26–28, 2001.
SAE Digital Human Modeling for Design and Engineering Conference and Exposition
Contact Paula Preston, SAE International, 400 Commonwealth Drive, Warrendale, PA 15096–0001, USA. Tel: +1–724–772–7131, Fax: +1–724–776–0002,
E-mail: meetings@sae.org, URL: http://www.sae.org/dhmc

# of events

Look for the Human Systems IAC exhibit at these meetings!

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Maui, HI, USA. July 28–August 2, 2001.
CAES 2001: International Conference on Computer-Aided Ergonomics and Safety
Contact Waldemar Karwowski, Center for Industrial Ergonomics, Academic Building, Room 445, University of Louisville, Louisville, KY 40292. Tel: +1–502–852–7173, Fax: +1–502–852–7397, E-mail: karwowski@louisville.edu, URL: http://www.ergonet.net/caes2001.html

New Orleans, LA, USA. August 5-10, 2001.
HCI International 2001: 9th International Conference on Human-Computer Interaction
Contact Kim Gilbert, School of Industrial Engineering, Purdue University, 1287 Grissom Hall, West Lafayette, IN 47907–1287, USA. Tel: +1–765–494–5426, Fax: +1–765–494–0874, URL: http://hcii2001.engr.wisc.edu

sep

Nashville, TN, USA. September 17–19, 2001.
2001 SAFE Annual Symposium
Contact SAFE Association, 107 Music City Circle, Suite 112, Nashville, TN 37214, USA. Tel: +1–615–902–0056, Fax +1–615–902–0077, E-mail: safe@usit.net, URL: http://safeassociation.org/2001.htm

Kassel, Germany. September 18–20, 2001.
8th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Human-Machine Systems (HMS 2001)
Contact Gunnar Johannsen. E-mail: hms2001@imat.maschinebau.uni-kassel.de, URL: http://www.imat.maschinenbau.uni-kassel.de/hms2001/time2.html

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Minneapolis, MN, USA. October 8–12, 2001.
45th Annual Meeting of the Human Factors and Ergonomics Society
Contact HFES, PO Box 1369, Santa Monica, CA 90406, USA. Tel: +1–310–394–1811, Fax: +1–310–394–9793, E-mail: hfes@compuserve.com, URL: http://hfes.org. *Proposals due March 19, 2001*

nov

Monterey, CA, USA. November 2001.
47th Biennial Meeting of the U.S. Department of Defense Human Factors Engineering Technical Advisory Group
Contact Sheryl Cosing, 10822 Crippen Vale Court, Reston, VA 20194, USA. Tel: +1–703–925–9791, Fax: +1–703–925–9644, E-mail: sherylynn@aol.com, URL: http://dticam.dtic.mil/hftag/. *Meeting is open to all government personnel and others by specific invitation*.

Discovering How Cognitive Systems Should be Engineered for Aviation Domains:
A Developmental Look at Work, Research, and Practice

Michael D. McNeese

Table 1. Categorical Structure of the Book Chapter.

Considering 15 Years Worth of What		
I.	What is it?	Defining Characteristics/Core Values
II.	What are the formative conditions?	Background/History/Perspective
III.	What are the objects of interest?	Use/Directions/Application
IV.	What are representative approaches/examples?	Theories/Methods/Approaches
V.	What has transpired?	Progress-Influences/Developing Stages
VI.	What has evolved/What has been learned?	Lessons/ Learned/Recombinate Themes
VII.	What is next?	Emerging Issues/Future Directions

As the old adage goes, "necessity is the mother of invention." A 15-year retrospective review of the author's work at Wright-Patterson Air Force Base provides the basis for discovering insights among the joint confluence of cognitive science, cognitive work analysis, cognitive modeling, cognitive field studies, and cognitive systems engineering (CSE) as relevant to military aviation domains. From early work involving the design of intelligent pilot-vehicle interfaces to current applications supporting collaborative activity in airborne warning and control systems (AWACS) operations, there is necessity to reinvent terms of engagement (see Table 1).

As part of this review/reinvention, a general framework (see Figure 1) highlights different emphasis areas taken by CSE practitioners. The framework conveys issues, models, methods, tools, application examples, and provides broad exposure to the question, "What is the use of cognitive systems engineering?" Using personal perspectives, developments, and case studies (as well as other practitioner approaches in CSE) a number of requirements, trends, and directions are discussed.

The categorical structure of the forthcoming report chapter, designed to address this basic-level question, is composed of a set of integrated queries (addressed across several personal stages of development that represent an order of emerging maturity).

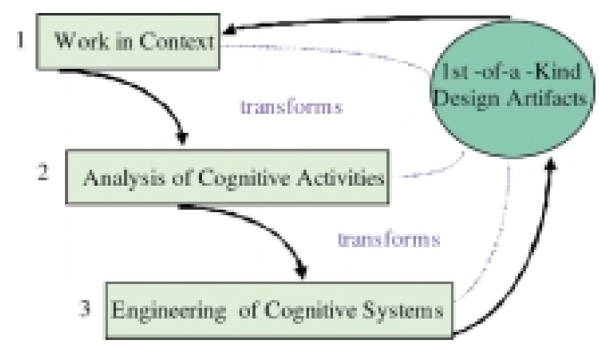

Figure 1. A general viewpoint of cognitive systems engineering.

As differing stages of personal development (in CSE) are explained in terms of challenges, themes, contributions, and streams of influences, significant advances are surveyed. The historical threads of ecological psychology, human factors engineering, and knowledge engineering are woven together to form a nexus from which these advances emerge.

To complement the historical significance of advances and integrate answers to the queries asked, a "living laboratory" approach (McNeese, 1996) is developed to enable CSE practitioners to become a community of learners. The living laboratory places value on discovery through different venues, concurrency, ecological validity, feedback, mutually informative processes, technological intervention, and the willingness to broadly

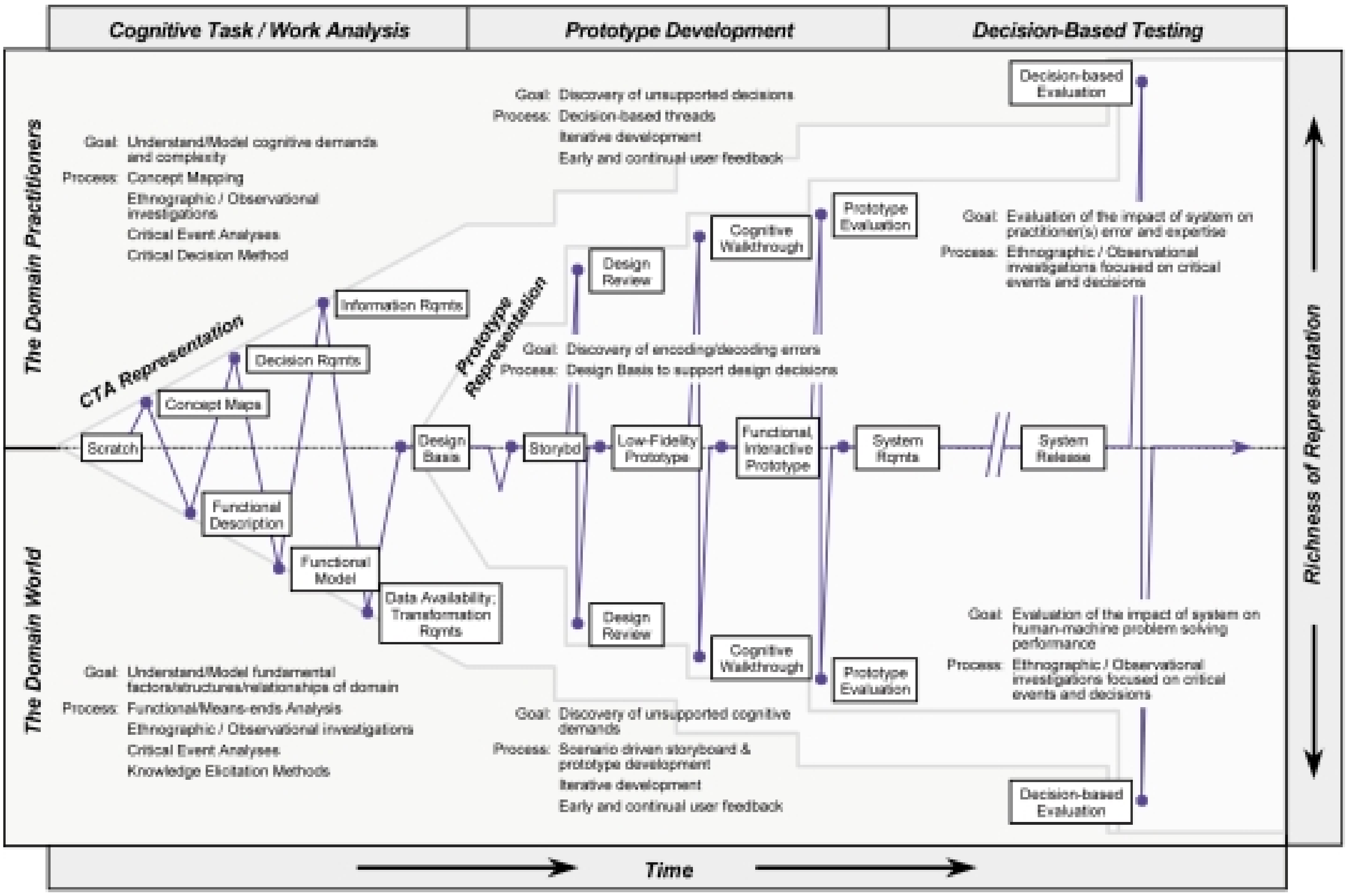

Figure 2. Conceptual basis for the Computer-Aided Cognitive Systems Engineering (CACSE) (Potter, Roth, Woods, & Elm, 1998).

approach complex problems without dogmatic, doctrinaire biases.

Two recent manifestations of the living lab view are the Computer-Assisted Cognitive Systems Engineering (CACSE) framework/toolkit (Potter, Roth, Woods, & Elm, 1998) and a new systematic approach for conducting cognitive field studies (McNeese, Bautsch, & Narayanan, 1999). CACSE will be briefly described here.

The CACSE tool integrates CSE and software engineering analysis for the purpose of creating innovative designs. Figure 2 shows the conceptual foundations underlying CACSE development. Tools such as CACSE can shape where CSE will lead. When coupled with strategies for cognitive field studies, foundations for knowledge as design are implemented.

Upon review of 15 years of work, research, and practice in CSE, the chapter concludes with a set of lessons learned and specific challenge points for practitioners that are posed to feed new trajectories for discovery. ■

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Balancing Practice-Centered Research and Design

David Woods and
Klaus Christoffersen

The intersection of people, technology, and work is of interest to many involved with research and development. Developers and technologists make claims about how a prospective new capability or new system development project will impact on performance. Sponsors are caught up in the sweeping dreams permitted by technology unfettered from harsh contexts of use, yet they fear software development projects that fail to provide useful tools or that create unanticipated negative effects. Practitioners and observers of practitioners at work note repeated forms of clumsiness in the technology deployed and unanticipated side effects of change. Researchers, blinded by the glare of disciplinary labels, drastically reduce situations to fit into a laboratory one variable at a time yet claim priority in the search for generic regularities. Human factors practitioners and usability engineers are called in too late to repair the connection between systems and use. Research results seem irrelevant to design. Design seems local and unique.

Research and development at the intersection of people, technology, and work is a world divided and hobbled. Innovation is tantalizing yet elusive. In the rush, we achieve only a cumbersome process of trial and error (publicizing the extent of design errors and failures would be bad for investment). The standard metaphor and organizational construct of the pipeline has failed given the possibilities for change and the predilection for new technology to demand connections across disciplinary boundaries. Research and development in this area is a world too often without effective interconnections and cross-stimulation.

We provide an alternative model at two levels. The first attribute is complementarity as a strategy for practice-centered research and design. This is the foundational strategy behind the label "cognitive systems engineering" (and related labels like "distributed cognition" and "naturalistic decision making") that makes it a substantive alternative to traditional disciplinary approaches. In other words, all of the new labels about the syntheses required to study and shape the intersection of people, technology, and work are only superficial exercises in career enhancement unless they provide substance to complementarity. Second, the model replaces the shopworn cliché of a research and development pipeline (a metaphor that may never have had substance) with synchronization of multiple, parallel cycles of learning and development that operate at different time scales. Interlocking these cycles is a difficult challenge (see Figure 1).

Researchers are connected to the systems development process by observing and abstracting patterns about the interaction of people, technology, and work. These researchers must be able to contribute concepts and techniques about what would be useful in the initial stages of a development cycle, but they are relaxed from the limited resource and time horizons that pressure development of real working systems.

Those working to advance technology for human interaction are connected to the systems development process by using or participating in studies of the actual effects of technology change. Rather than just measure success in terms of autonomous machine capabilities, they can look to the research base for empirically based patterns and models about how technology developments support effective collaboration with human practitioners.

Effective innovation in system development depends on having technological advances to draw on and on having concepts about what may be useful to support human performance available early in a development cycle to be able to identify leverage points and to anticipate side effects of change. In effect, the balancing

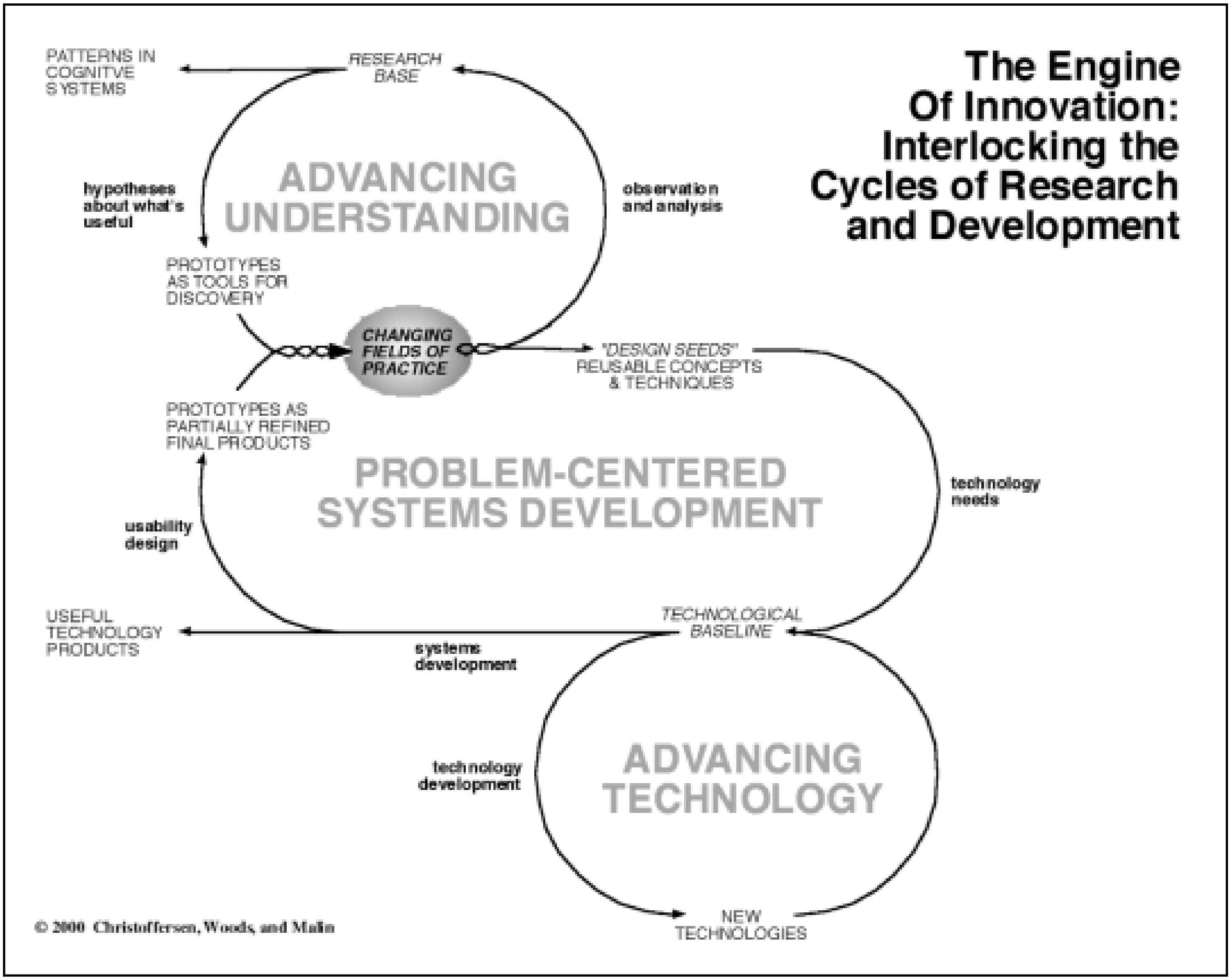

Figure 1. The engine of innovation: Interlocking cycles of research and development.

act needs mechanisms to support *distributed innovation*. This is an example of the area of human-machine systems called "computer-supported collaborative work." Usually this work is directed at practitioners, designers, or managers. Here the need is to use principles for collaborative work and the technology infrastructure for connectivity to support distributed innovation. Doing this, as is building any kind of collaboration, requires energy and investment in coordinated activities across the multiple parallel cycles. ■

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Bridging the Gap Between Cognitive Analysis and Cognitive Engineering

Emilie M. Roth, James Gualtieri, James Easter, Scott S. Potter, and William C. Elm

There has been growing interest in using cognitive task analysis (CTA) to understand the requirements of cognitive work (Schraagen, Chipman, & Shalin, 2000; Vicente, 1999). While CTA techniques have proved successful in illuminating the sources of cognitive complexity in a domain, the results of the CTA are often only weakly coupled to the design of support systems (Potter, Roth, Woods, & Elm, 2000). A critical gap occurs at the transition from CTA analysis to system design, where insights gained from the CTA must be translated into design requirements.

In this paper we describe an approach to bridging this gap and present a visualization that we developed for a military command application as a concrete illustration of the approach.

Our approach is predicated on the premise that the design of advanced visualizations and decision-aids must be grounded in an understanding of the domain of practice and the demands it imposes on domain practitioners. Design activities include:

- Capturing the critical domain relationships that define the problem-space that the domain practitioners confront;
- Identifying the cognitive tasks and critical decisions that arise in the domain and require support;
- Identifying the information requirements for these cognitive tasks and decisions;
- Defining the relationships between decision requirements and associated information requirements and user interface design concepts;
- Exploring techniques to implement these design concepts into powerful visualizations of domain semantics.

Figure 1 (see page 15) provides a visual depiction of the sequence of design activities and associated design artifacts. These design artifacts create a continuous design thread that provides a principled, traceable link from the demands of the domain as revealed by the CTA, to the cognitive and collaborative processes that require support, through the elements of the decision aid that explicitly address those support requirements.

We recently created an innovative visualization to support military commanders in choosing combat power to achieve mission objectives using this design approach. The display was developed as part of the DARPA Command Post of the Future program (Logica Carnegie Group, 2000), and provides a concrete illustration of how intermediate design artifacts can be used to provide a principled, traceable link from cognitive analysis to design. The “choose combat power” display represents one of a growing number of examples of successful systems that have been developed using a domain analysis approach (e.g., Roth, Lin, Kerch, Kenney & Sugibayashi, in press; Potter, Roth, Woods & Elm, 2000). ■

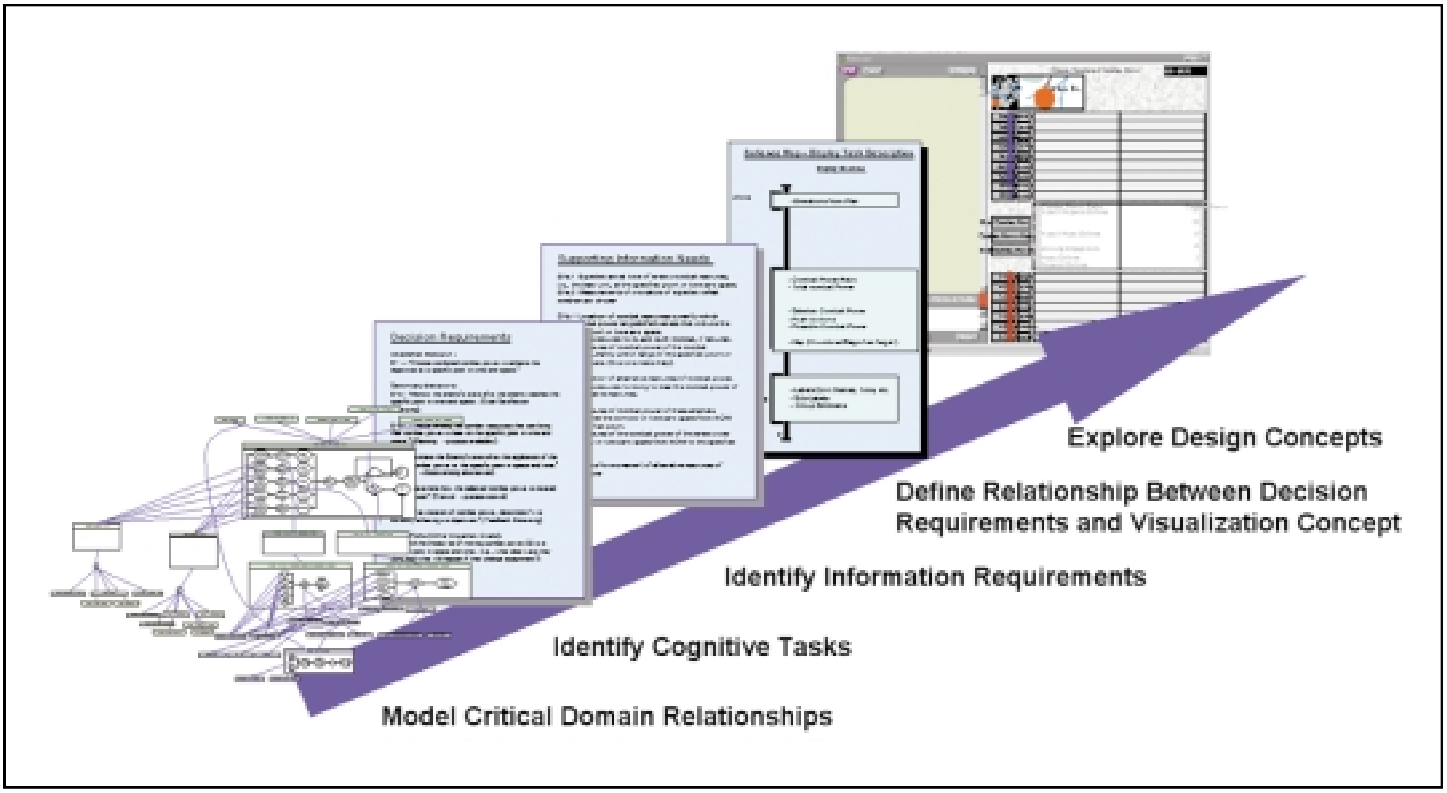

Figure 1. A sequence of linked design artifacts is used to create a continuous design thread that starts with a representation of domain relationships through development of decision support requirements to creation of visualization and aiding concepts and rapid prototypes with which to explore the design concepts.

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Cognitive Work Analysis for Air Defense Applications in Australia

Neelam Naikar, Gavan Lintern, and Penelope Sanderson

Cognitive work analysis (CWA) is one of the possible tools that a cognitive systems engineer can use for analysing, modeling, designing, and evaluating complex systems. The specific focus of CWA is on supporting worker adaptation and flexibility in complex, real-time work domains, especially during unanticipated situations. CWA is therefore particularly well suited to military domains where opposing forces deliberately create unexpected situations to gain a tactical advantage. With this in mind, Australia's Defence Science and Technology Organisation (DSTO) has used CWA in a variety of military aviation contexts.

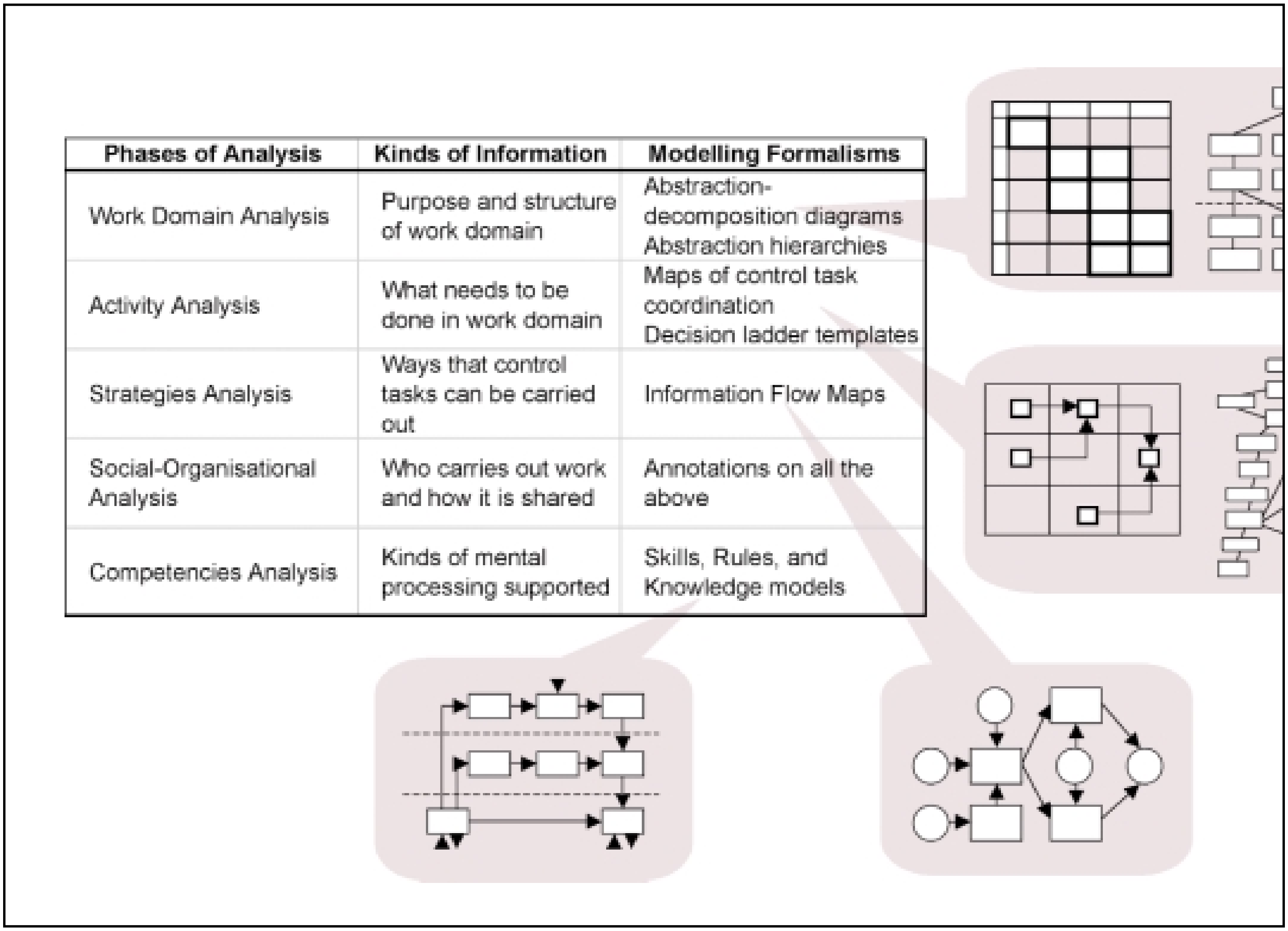
A complete CWA typically consists of five phases (see Figure 1 on page 17):

- Work domain analysis which focuses on the functional purposes, priorities and values, purpose-related functions, physical functions, and the physical objects of a system;
- Control task analysis which focuses on the activity that must occur in the work domain for a system to achieve its functions and purposes;
- Strategies analysis which focuses on ways the tasks or activities may be carried out;
- Socio-organizational analysis which focuses on who carries out the work and how it is shared; and
- Worker competencies analysis that focuses on the knowledge, training, capabilities, and expertise that workers need to carry out the work of the system.

All of the phases of CWA are potentially useful throughout a system's life cycle, although some phases of CWA may be more useful than others at different points in the life cycle. For example, during the initial stages of a system's life cycle work, domain analysis is useful for defining requirements because it identifies why a new system is needed, what its environmental context will be, and what functions must be implemented. However, more detail about the activity of the system is needed during the specifications stage at which point a control task analysis becomes an important contributor. During the system design stage, all components of a CWA are typically expected to contribute. The various phases of CWA can also be used for evaluating competing designs, defining training requirements, and considering potential upgrades. Finally, CWA can also help to support a decision to retire a system when a work domain analysis of the broader work context shows that the current system is no longer needed or competitive.

Research at DSTO has demonstrated several of the potential benefits of CWA. One of the most successful applications of CWA was to Australia's acquisition of a fleet of airborne early warning and control (AEW&C) aircraft. A work domain analysis of AEW&C was used to evaluate competing designs from three potential manufacturers. This approach fostered an integrated evaluation of the three designs by the AEW&C Project Office. It also allowed the Project Office to express the results of the evaluation in terms of military utility as opposed to technical properties. Moreover, the work domain analysis served as a "sanity check" because it supported an explicit evaluation of the impact of physical design properties on higher-level functionality. CWA has also contributed to the analysis of AEW&C activities and the evaluation of AEW&C human-system integration and automation. In addition, DSTO researchers have also been successful in using CWA to define training needs in support of the Australian Defence Force's acquisition of a training system for the F/A–18 fighter aircraft.

In conclusion, within the context of military aviation, DSTO has found that CWA has provided valuable insights concerning matters such as interface design, training program specification, research program design, intelligent agent modeling, and so forth. The products of CWA have also been found to be reusable for different purposes



Phases of Analysis	Kinds of Information	Modelling Formalisms
Work Domain Analysis	Purpose and structure of work domain	Abstraction-decomposition diagrams Abstraction hierarchies
Activity Analysis	What needs to be done in work domain	Maps of control task coordination Decision ladder templates
Strategies Analysis	Ways that control tasks can be carried out	Information Flow Maps
Social-Organisational Analysis	Who carries out work and how it is shared	Annotations on all the above
Competencies Analysis	Kinds of mental processing supported	Skills, Rules, and Knowledge models

Figure 1. Five phases of CWA with iconic representations of their most familiar analytic products

over a system's life cycle. Furthermore, CWA has become an intellectual framework at DSTO within which human factors practitioners, training specialists, simulator builders, cognitive scientists, and operations researchers can communicate and dovetail their activities.■

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Analyzing the Cognitive System From a Perceptual Control Theory Point of View

Keith C. Hendy, David Beevis,
Frederick Lichacz, and
Jack L. Edwards

A closed loop, negative loop gain, feedback system is an error-correcting system. The inverse of this proposition is that all error-correcting systems can be reduced to a closed loop, negative gain, feedback system. If these propositions are true, and the human is seen as exhibiting error-correcting behavior, then William T. Powers' claim that all human behavior occurs as a result of a perceptually driven, goal referenced, feedback system (Powers, 1973), should come as no surprise. This is the tenet of Perceptual Control Theory (PCT), depicted in Figure 1. At best PCT provides a truthful explanation of how humans form and emit behaviors; at the very worst PCT is a normative model of human behavior.

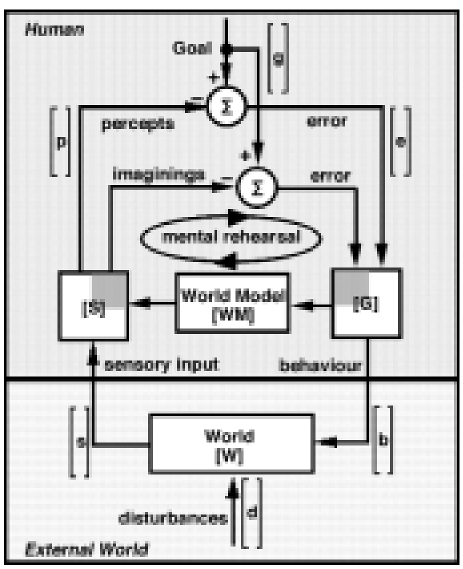

Figure 1: The Perceptual Control Theory (PCT) model.

The PCT model suggests a multilayered system, with multiple goals providing the reference points for a hierarchical organization of control loops. These loops provide control at many levels—from the lowest levels of sensory processing, upward to the satisfaction of abstract goals such as the need for self-esteem and actualization. In PCT terms, an emitted action or behavior is in response to the presence of an error, or difference, signal. The emitted action is transmitted purposefully, with the intention of changing the state of the world so that the operator's perception can be made to match a desired state or goal. This reduces the error signal to zero. The constraints on human information processing, within the modules of the PCT loop, are described by the Information Processing (IP) model (Hendy, Farrell, & East, 2000; Hendy, Liao, & Milgram, 1997). Together the IP/PCT models provide a strong integrating framework for analyzing and predicting human information processing behaviors (Hendy & Farrell, 1997).

The starting point for the design of any complex system should be analysis. For systems where human functions are predominantly "cognitive," the method of analysis should capture this essentially human activity. Traditionally, human engineering analyses have been based on a hierarchical decomposition of system missions, functions, and tasks (MFTA). Perceptual Control Theory, together with the IP model, provides a theoretical framework for guiding this process. PCT reorientates the approach from a serial process of function analysis, function allocation, task analysis process, to an integrated process of a hierarchically directed goal analysis (or HGA). PCT–HGA combines the previously separate processes into a single unified process. With PCT it is inescapable that goals at all levels are candidates for assignment to an agent (human or machine). This is a major point of departure between traditional MFTA and the IP/PCT-based method.

Two new analyses emerge from the PCT framework. The first, a stability analysis, looks to see if certain external variables can be simultaneously under multiple control. If conflicting goals or incompatible internal perceptual, cognitive, or machine functions could cause these multiple control situations to be unstable, then the designer has to find a way to separate control or otherwise

ensure stability. The second analysis looks at the upward flow of information in the system. Each goal is examined to see how information existing at the subgoal level flows up to the level above. Both analyses potentially identify new goals that must be accommodated by interface design.

A PCT-based HGA was performed on a single segment of a land forces command and control environment that had previously been analyzed by traditional MFTA. The PCT-based HGA identified 37 additional activities that had been missed in the original analysis. The success of the PCT analysis in identifying additional goals, missed in the traditional MFTA, is heartening. The new goals were all associated with support to higher level intent. For this particular application, it would seem that established command and control procedures had largely addressed the issue of stability, as the potential for simultaneous control was not a factor in the analysis of this segment of operation. ■

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Cognitive Cockpit Engineering: Coupling Functional State Assessment, Task Knowledge Management and Decision Support for Context Sensitive Aiding

Robert M. Taylor, Michael C. Bonner, Blair Dickson, Howard Howells, Christopher A. Miller, Nicholas Milton, Kit Pleydell-Pearce, Nigel Shadbolt, Jeni Tennison, and Sharon Whitecross

Future offensive air systems will be highly automated, but human involvement will still be needed. In complex, rapidly changing military environments maintaining effective human cognitive involvement is a significant challenge. A human-centered approach to system design is needed that is based on human cognitive requirements. Pilot judgment provides context sensitivity that is hard to automate. In air systems involving high levels of automation, rather than replacing the pilot, technology is needed to assist the future aircrew in cognitive work. To be responsive to changing mission requirements, in particular for in-flight situation assessment and mission replanning, adaptive and context-sensitive support will be needed. To be responsive to the changing requirements of the human operator, technology also needs to be influenced by the individual's physiological and behavioral state. This would adaptively respond to indications of overload, distraction or performance difficulty, and to the possibility of incapacitation in flight, providing a pilot safety net.

Recognizing this challenge, the UK Ministry of Defence (MOD) in conjunction with the Defence Evaluation and Research Agency (DERA) are conducting a three-year program of applied research in cognitive engineering looking at intelligent knowledge-based decision aiding for military fast jet pilots. The Cognitive Cockpit (COGPIT) project (see Figure 1) seeks to couple cognitive technologies for pilot functional state assessment and knowledge-based systems for situation assessment and decision support with concepts and technologies for adaptive automation and cockpit adaptive interfaces.

Pilot functional state monitoring is in its infancy in providing on-line measurement for task adaptation. In contrast, task knowledge management and decision support for context-sensitive aiding involves the application of relatively mature technology. Coupling these should provide a system capable of recognizing the need for automation to achieve a mission objective and of providing instructions to the operator on how to achieve it, and/or implement the required automation. Initial development work indicates that on-line pilot functional state assessment is feasible with current computing power and could provide useful information for cockpit and task adaptation. In particular, the increased power of individual profiles for developing customized adaptations seems a highly promising development.

The work shows how a knowledge engineering methodology can provide useful on-line knowledge-based systems (KBS) support for pilot replanning tasks, with potential for wider application. The traditional knowledge acquisition bottleneck has been significantly reduced by the provision of a structured methodology and tool set. Demonstration has highlighted the criticality of the timing of KBS advice in context. The work has also shown how useful assistance in the management of cockpit interfaces, tasks, and automation can be provided by a tasking interface system based on a shared task model. The development of an effective *tasking interface manager* with which pilots can interact easily, is critical. Although it is relatively easy to track tasks instantiated in a mission plan, it becomes very difficult to track tasks that deviate from the plan. Tracking deviations requires the system to infer pilot intent, which is problematic.

Figure 1. Initial conceptual prototype for the DERA Cognitive Cockpit.

Current cockpit work seeks to identify the precise methods for cockpit adaptation and their benefits and to determine the optimization of control/display interfaces, in particular for voice dialogue, and the helmet-mounted display and 3D audio ramifications. A key step has been the design of a use-centric system for cognitive control of levels of adaptive automation that avoids unwanted automation surprises.

The COGPIT project has responded to the challenge of increasing automation in a complex environment where human involvement is needed in critical decisions. In seeking to couple cognitive technologies for pilot aiding with extensive use of cognitive engineering methods, the project provides a particularly human centric approach to use-centric design. The benefits of real-time decision support, and on-line cockpit task adaptation, seem likely to become evident and realizable in the near future. But, it seems that further work will be needed to provide the benefits of real-time adaptation to cognitive functional state. ■

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Beyond Cognitive Engineering:
Assessing User Affect and Belief States to Implement Adaptive Pilot-Vehicle Interaction

Eva Hudlicka and
Michael D. McNeese

The mutual influence of cognitive schemata and contextual constraints is considered the accepted basis for cognitive system engineering practices (Rasmussen, Pejtersen, & Goodstein, 1994). Less generally accepted is the fact that affective states can also dramatically influence human performance and decision making via effects on attention, perception, situation assessment, and ultimately action selection (LeDoux, 1992; Williams, Watts, MacLeod, & Mathews, 1997).

Currently few human-machine systems attempt to dynamically assess and adapt to the users' affective and belief states. This shortcoming can lead to nonoptimal behavior at best and critical errors with disastrous consequences at worst. This is increasingly evidenced by a variety of accidents and incidents broadly attributed to "human error" that exist in a number of settings, including military aviation, where conditions of heightened stress are common.

To address these challenges, we developed an Affect and Belief Adaptive Interface System (ABAIS). ABAIS uses a methodology designed to adapt the human-machine interface to the user's affective state and situation-specific beliefs that might influence performance (Hudlicka & Billingsley, 1999). The methodology consists of four steps: sensing/inferring user's affective state and performance-relevant beliefs; identifying their potential effects on performance; selecting a compensatory strategy; and

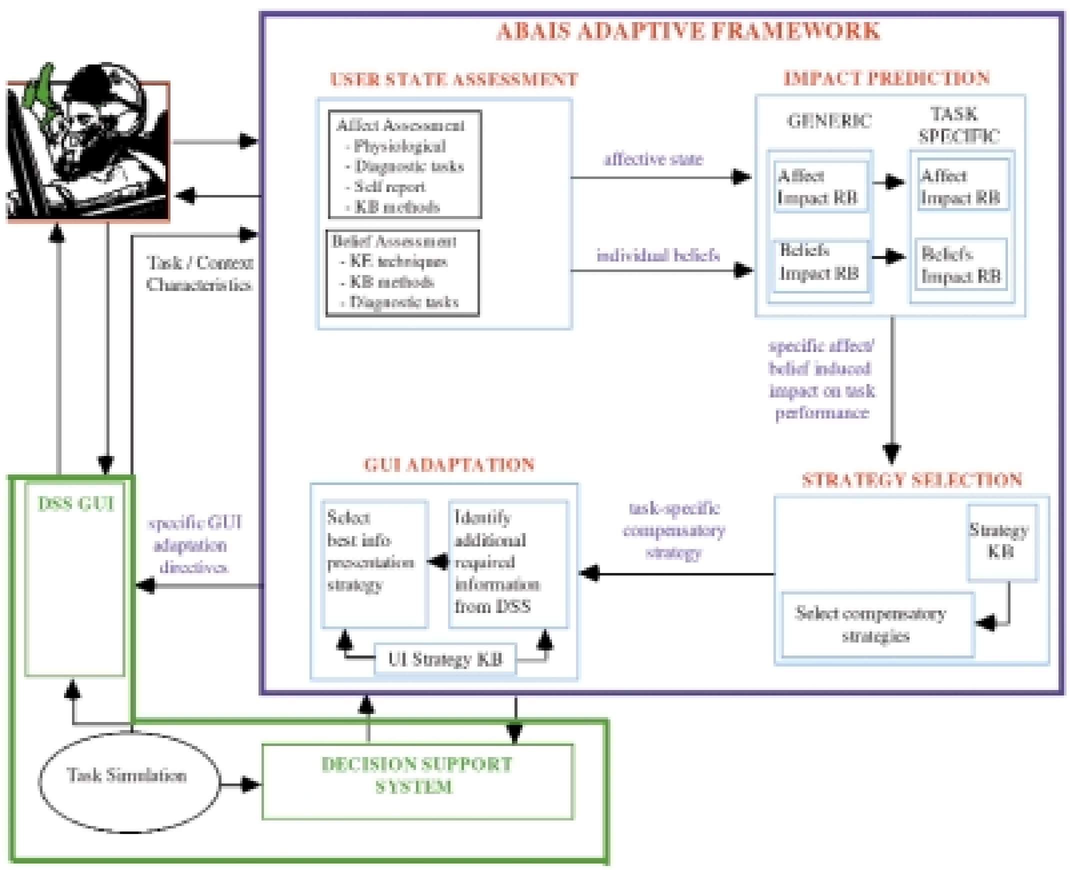

Figure 1. ABAIS architecture implementing the affect-belief adaptive methodology.

implementing this strategy in terms of specific graphic user interface (GUI) adaptations.

The ABAIS prototype implements this methodology in terms of an architecture shown in Figure 1. The architecture consists of four modules: User State Assessment provides a framework for integrating a variety of methods to identify the user's affective and belief state (e.g., knowledge-based, self-reports, diagnostic tasks, physiological sensing). Impact Prediction integrates generic empirical findings with the results of task-specific Cognitive Affective Personality Task Analysis (CAPTA) (Hudlicka, 2000) to predict the most likely effects of user states on performance. Strategy Selection combines the CAPTA results with individual preferences to derive an appropriate compensation strategy. Finally, GUI Adaptation implements this strategy by modifying the content and/or format of the user interface (see Figure 2).

The ABAIS prototype was developed and demonstrated in the context of an Air Force combat task simulation. ABAIS assessed the pilot's anxiety and belief states via a knowledge-based approach using information from a variety of sources (e.g., task characteristics, pilot personality, etc.), predicted the effects of user state on performance, and suggested and implemented specific GUI adaptation strategies based on the pilot's information presentation preferences (e.g., modified icon/display to capture attention, etc.).

Preliminary results indicate feasibility of the ABAIS approach, raise a number of further research questions, and suggest specific requirements for a successful, operational affect and belief adaptive interface (e.g., limiting the number, type, and resolution of affective and belief states; using multiple methods and individualized data for user state assessment; implementing "benign" adaptations—adaptations should never limit access to existing information).

This work represents an attempt to move beyond the traditional cognitive and psychophysical factors in designing human-machine interfaces by explicitly integrating affective and personality considerations into the design process via CAPTA. While the initial prototype was developed within a military aviation task context, we believe that the results are applicable to a broad variety of nonaviation and nonmilitary domains.■

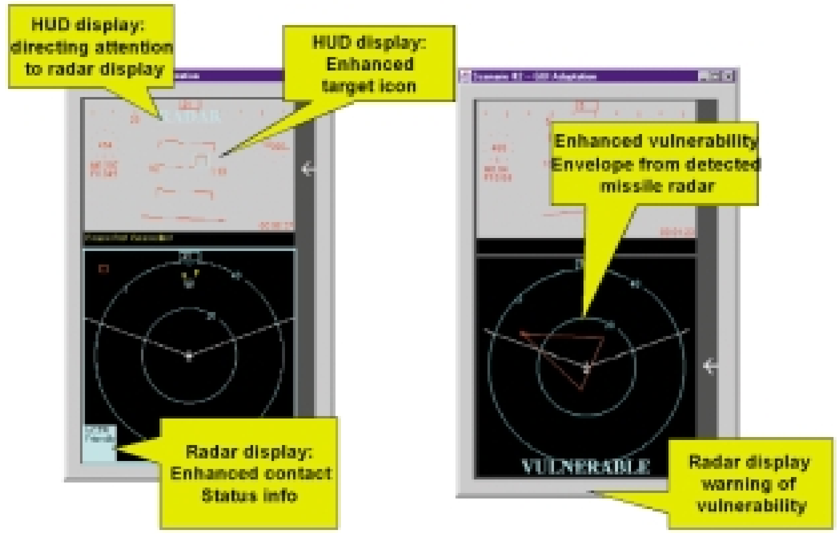

Figure 2. Summary of GUI adaptations.

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